Examining the functionality of peripheral vision: From fundamental understandings to applied sport science

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REPORT

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ABSTRACT

In sports, it is important not only to locate gaze on the right location to utilize the high acuity of foveal vision, but also to attend to other objects in the environment without looking directly at them, accordingly, using peripheral vision. Peripheral vision becomes especially important if, for example, the processing of information from more than one location (e.g. players) is decisive in making accurate decisions. Since such decisions generally must be made under high spatio-temporal demands, costly eye-movements might be advantageously avoided by using peripheral vision for information pick-up from multiple cues. In a series of studies, we aimed to translate the demands found in sports and to investigate the functionality of peripheral vision in a well-controlled experimental paradigm, the multiple object tracking (MOT) task. MOT was implemented in a dual task, along with an additional event-detection task. The present article first presents an overview of sport-specific studies focusing on the functionality of peripheral vision and following, summarizes a series of three published MOT studies. These studies show that peripheral vision is used for simultaneous target monitoring and target-change detection and that visual and attentional demands affect gaze anchoring and change-detection rates. Results also reveal a dysfunctionality of saccades, and further suggest an event- and distance-optimized gaze-anchoring position. In the final portion of this article, we derive specific applications for future sports-specific research. Specifically, we suggest to: (a) use dual-task situations in sport-specific settings, such as monitoring multiple players in soccer and playing a pass at specific moments, (b) investigate the costs of saccades in sports situations with high spatio-temporal demands, as in martial arts, and finally, (c) manipulate attentional and visual demands. For each of these avenues of research, we sketch sports-specific experiments currently being conducted in our research group.

Keywords:
pivot point – gaze anchoring – change detection – multiple object tracking – eye tracking

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Introduction

The processing of detailed visual information is limited by the properties of the visual system. Specifically, only 1-2 arc degrees or 1% of the entire retinal surface is equipped with a large number of cones (Williams, Davids, & Williams, 1999, p. 91), such that when stretching one's arm forward with the thumb up, nearly only the thumbnail can be perceived as perfectly sharp by foveal vision (or central vision as opposed to peripheral vision). This limitation has considerable consequences for visual search behavior, especially in sports games like soccer or basketball. In these sports, a number of objects in the visual environment are relevant (e.g., teammates, opponents and ball). These objects can either be scanned with foveal vision, allowing for detailed information processing of single locations, or be monitored with peripheral vision, allowing for simultaneous information processing of multiple locations (Davids, 1984; Williams & Davids, 1998). Scanning the environment with foveal vision comes with the disadvantageous consequences of gaze shifts, called saccades, which always result in a temporary suppression of visual information processing (Bridgeman, Hendry & Stark, 1975; Burr & Morrone, 1996; Burr, Morrone, & Ross, 1994; Klingenhoefer & Bremmer, 2011; Matin, 1974). Although the intervals of saccadic suppression are not consciously perceived and last no longer than approximately 200 ms (Matin, 1974, p. 912), such intervals become increasingly relevant when considering fast sports movements, like jabs in boxing or smashes in table tennis, that may have even shorter movement duration. Therefore, especially in sports with high spatio-temporal demands, the interrupted information pick-up could significantly impair motor performance. To avoid detrimental suppression effects, peripheral vision could be rather functional for the control of motor behavior.

In this report, we will first provide some examples of sport-specific studies that discuss the role of peripheral vision and, subsequently, explain the frequently used methods of its investigation. It will become apparent that the simultaneous investigation of gaze location and attention is difficult. Therefore, here, we will summarize three experimental studies in which we used an experimental paradigm that supports both the examination of the functionality of peripheral vision as well as the simultaneous testing of gaze location and attention. Finally, we will give some examples of how this paradigm can be translated to sports and test the functionality of peripheral vision in more applied settings.

Studying peripheral vision in sports

A number of studies have focused on the functionality of peripheral vision in sports. For example, Williams and Davids (1998) investigated the pick-up of information from peripheral locations in a video-based 3 vs. 3 soccer decision-making task. With eye-tracking measurements in the first experiment, they were able to determine that experts and novices frequently locate their gaze at the hip location of the direct opponent. In the second experiment, where participants had to verbalize their thoughts while observing situations, experts were found to pick-up more information from peripheral locations. These results show that peripheral vision seems to be used if information from multiple locations needs to be processed. In a recent field study by Milazzo, Farrow, Ruffault, and Furnier (2016), elite and novice karate fighters had to react to attacks in different fighting scenarios. Results revealed that elite fighters spent more time fixating the head and the torso of the opponent than did the novice fighters, who spent more time fixating the pelvis and the front hand. Thus, the authors concluded that while anchoring gaze at the head or the torso, elite figthers rely more on peripheral information to detect movements from/in the periphery than would novices. In other studies that observed gaze to be reliably anchored at a location *between* relevant cues, information pick-up could supposedly depend on peripheral vision. Such a point is often called a "pivot" or an "anchor", and is assumed to be beneficial for decision-making performance. For example, soccer goalkeepers have been found to often fixate a position between the ball and the shooting leg when attempting to save a penalty kick (Piras & Vickers, 2011; Savelsbergh, Williams, Kamp, & Ward, 2002). In other sports, such a pivot could be the pitcher's elbow during the throwing phase of a baseball pitch (Kato & Fukuda, 2002) or the location between the setter's hands and the ball when defending in beach volleyball (Vansteenkiste, Vaeyens, Zeuwts, Philippaerts, & Lenoir, 2014). Generally, it is assumed that directing gaze to pivot or anchor points facilitates the use of peripheral vision for the pick-up of motion information from multiple relevant areas (Abernethy, Gill, Parks, & Packer, 2001; Ward, Williams, & Bennett, 2002).

Many studies examining the functionality of peripheral vision did not *a priori* aim to compare foveal and peripheral vision, but rather *a posteriori* interpreted the obtained findings with respect to peripheral vision to explain, for example, why gaze was not located on specific cues. To investigate the role of peripheral vision in sports, a variety of qualitative and quantitative approaches have been applied, specifically, (a) verbal reports, (b) the occlusion paradigm or (c) the moving-window/mask paradigm.

(a) *Verbal reports* require participants to name informative areas in the visual environment to indicate the actual location of their visual attention (e.g., Buckholz, Prapavesis, & Fairs, 1988; Williams & Burwitz, 1993; Williams & Davids, 1998; Vickers, 1988). Verbal reports are conducted either after (retrospective report) or during (concurrent report) the completion of a task. For example, Williams and Burwitz (1993) used retrospective reports to investigate the information sources of soccer goalkeepers and found that goalkeeper's decisions are affected by information gathered from the penalty-taker's hip location and the orientation of the foot prior to ball contact. Concurrent verbal reports were used, for instance, by Williams and Davids (1998, Experiment 1) who showed that in a 3 vs. 3 decision-making task, experienced soccer players are able to verbalize more information from peripheral locations than can less experienced soccer players. Both groups showed the same visual search behavior, meaning that participants mostly fixated on the player in possession of the ball and did not switch to cues in the periphery. The verbal-report approach, however, has been criticized since subjects could be affected by participants' *a priori* expectations (Williams, Davids, & Williams, 1999) or by attempts to rationalize previous situations (Green, 1995). Additionally, verbalizing the actual information used for decision-making may be difficult (Nisbett & Wilson, 1977), perhaps due to a preconscious processing of ambient information (Previc, 1998). Thus, retrospective and concurrent verbal reports should be mainly regarded as methods for identifying objects or locations that gain attention, but not as a comprehensive tool for unveiling which information is processed through peripheral vision.

(b) A second approach for directly examining peripheral vision is the *occlusion paradigm*. Empirical studies have compared performance in conditions with and without occluded areas in the periphery to examine the relative effect of peripheral information on decision-making (e.g., Hagemann, Schorer, Canal-Bruland, Lotz, & Strauss, 2010). Since experts are expected to make more use of parafoveal and peripheral information than near-experts or novices (Gegenfurtner, Lehtinen, & Säljö, 2011), the expert-performance advantage should decrease when information-rich areas in the periphery are occluded. Exactly this finding was reported by Williams and Davids (1998, Experiment 2), who found less pronounced expert advantages in a defensive soccer task when opponents in the periphery were occluded, thus highlighting the general importance of peripheral information in this task. However, spatial occlusions of the visual environment may *generally* impair decision-making of experts (Hagemann et al., 2010). Therefore, as potentially crucial perceptual information is withdrawn, the occlusion paradigm may not be ideal for investigating the relevance of peripheral vision in sports because it may not allow for the determination of the truly important information from peripheral vision (Mann, Williams, Ward, & Janelle, 2007).

(c) In the third approach to studying peripheral vision in sports, the *moving-window/-mask paradigm* (or the *gaze-contingent display-change paradigm*; McConkie & Rayner, 1975), the position of gaze is linked to a moving window or mask that specifically controls the accessibility of the visual field. In the context at hand, the most interesting conditions are with the blurring or even complete elimination of either peripheral information (moving window) or foveal information. In contrast to the occlusion paradigm discussed before that removes specific areas or objects, it is now the eye movements of the observer that influence which areas in the visual field are occluded (or blurred) by the moving window or mask. In this experimental set-up, the use of peripheral vision would be indicated by selectively impaired performance in the moving-window condition, while the use of foveal vision would be indicated by that in the moving-mask condition (Ryu, Abernethy, Mann, Poolton, & Gorman, 2013; Schorer, Rienhoff, Fischer, & Baker, 2013). Applying exactly this approach in a basketball decision-making task, Ryu et al. (2013) found superior performance of experts compared to novices *independent* of the viewing conditions (full image, moving window, moving mask), implying that experts and novices seem to use peripheral vision to the same extent. Interestingly, the authors also report decreased saccadic amplitudes in the moving-window but not in the moving-mask condition, which they attribute to the inability to plan the location of the next fixation due to the loss of peripheral vision. This highly plausible explanation is substantiated by the claim that, before the initiation of a saccade, attention is located at the position of the subsequent fixation (Finlay, 1982; Nuthmann, 2014). Therefore, in a follow-up study, Ryu, Abernethy, Mann, & Poolton (2015) used different levels of visual blur instead of opaque occlusions. Again, in comparison to the full-image condition, changes in saccadic gaze-behavior were found for even the mildest levels of blur. However, due to this resulting behavioral change, it seems difficult to draw inferences on the functional role of peripheral vision under *normal* viewing conditions.

MOT as a novel approach to peripheral-vision research

As outlined before, the traditional approaches to studying the role of peripheral vision in sports are afflicted with some limitations. Therefore, before settling with verbal measures (verbal reports) or changing the available visual information (occlusion paradigm and moving-window/-mask paradigm), it might be worthwhile to return to the fundamental demands found in sport-specific tasks that substantiate the great relevance of peripheral vision. First off, the requirement to simultaneously monitor a number of teammates or opponents and respond to players' actions detected in the periphery plausibly depends on peripheral vision (cf. Ryu et al., 2013, 2015; Williams & Davids, 1999; Williams, Janelle, & Davids, 2004). Further, peripheral vision is expected to play an important role in situations requiring the processing of motion-related information (Bahill & LaRitz, 1984; Bahill & Baldwin, 2004; Haywood, 1984; Williams & Elliot, 1999).

Consequently, an experimental paradigm that creates a dual-task situation with both the monitoring of multiple objects and the concurrent detection of object changes would be valuable. Additionally, the task should have a high level of experimental control while still allowing for natural gaze behavior, meaning that participants should not be instructed to gaze at a fixation cross as is typically the case in controlled laboratory conditions (e.g., Luu & Howe, 2015). Based on these requirements, the *multiple object tracking* (MOT) task, first introduced by Pylyshyn and Storm (1988), seems to be appropriate. In this task, participants are asked to track a number of designated moving targets among identical distractors and to recall the targets at the end of each trial (Figure 1).

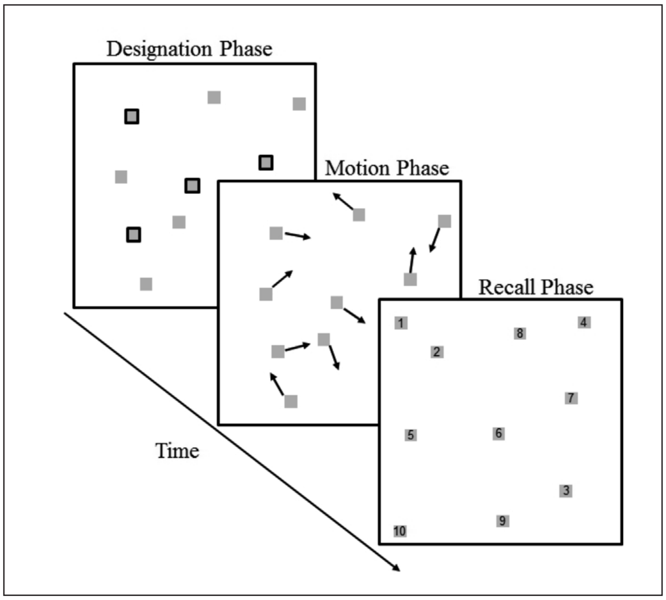

Figure 1: The three characteristic phases of the MOT task. The to-be-tracked targets are highlighted in the designation phase. Then, all targets and distractors move randomly over the subsequent motion phase. In the final recall phase, the initially cued targets must be identified by naming the respective numbers projected on the objects (cf. Vater et al., 2017a).

Several fundamental tracking mechanisms of MOT performance have been discussed in the literature (for an overview, see Oksama & Hyönä, 2004). Predominantly, previous MOT research has shown that gaze is regularly directed towards the virtual center of mass of the polygon formed by the moving targets (Fehd & Seiffert, 2008, 2010; Zelinsky & Neider, 2008). One explanation for this gaze behavior is that the observer groups the targets into a virtual polygon, such that the center of one virtual object is tracked rather than multiple single objects (Yantis, 1992). In the context at hand, this centroid strategy is of particular interest as it allows for the experimental control of the participant's point of gaze without specific gaze instructions (e.g., to fixate a fixation cross). In turn, events can be experimentally manipulated to occur at defined distances from the MOT targets' centroid (i.e., the location of the expected gaze point). Hence, with events in which a target temporarily changes its form or movement, the team-sports' real-world demands of monitoring several players and concurrently making decisions based on an opponent's sudden change in posture (form) or movement direction (motion) would be matched by the MOT/change-detection dual-task. Moreover, as this setup allows for the experimental manipulation of peripheral-vision conditions, the MOT paradigm together with a change-detection task might be transferable to sports.

MOT/change-detection dual-task research on peripheral vision

In a series of three studies, the MOT task and the secondary change-detection task were used to test the functionality of peripheral vision under task demands characteristically identified in sports situation that typically require peripheral vision. In study 1, we examined whether peripheral vision is indeed used to monitor moving objects and detect motion changes. Study 2 tested participants' ability to use peripheral vision in dual-task situations, and, finally in study 3, attentional and visual demands were systematically manipulated to investigate how each affect gaze as well as monitoring and change-detection performance. Below, the three studies are introduced in more detail.

Monitoring multiple moving objects with peripheral vision

In the first study, conducted by Vater, Kredel and Hossner (2016), the utility of peripheral vision for target monitoring in MOT was investigated. Particular to this study compared to most traditional MOT experiments, a more sport-relatable setting was used that employed a large screen (height: 1.87 m; width: 3.01 m) rather than a small computer monitor. This set-up further necessitated the application of a motion-capture integrated eye-tracking device. This setup as well as a replication of previous MOT studies by Fehd and Seiffert (2008, 2010) showing a centroid-looking gaze behavior was evaluated in Experiment 1 of the study. To test the ability to detect motion changes with peripheral vision, Experiment 2 examined whether target-motion changes are detected better than target-form changes in the periphery. If participants detected a change in any of the highlighted targets, they had to immediately press a button and then name the number of the target that changed in form or motion at the end of the trial. If the button was pressed before gaze was on that target, peripheral vision was used for change detection. Since previous research has shown that motion-information changes facilitate the use peripheral vision (To, Regan, Wood, & Mollon, 2011), target-motion changes should be well detectable with peripheral vision, even as motion perception becomes incredibly less sensitive with increasing eccentricity (Bower, Bian, & Andersen, 2012; McKee & Nakayama, 1984; Yu et al., 2010). Due to the impaired acuity of peripheral vision in comparison to foveal vision, for form and motion changes of comparable salience, higher detection rates for target-motion than target-form changes were expected (for further details on the methods, see Vater et al., 2016).

The results of Experiment 1 successfully replicated results of previous studies observing the expected centroid-looking strategy in MOT. Gaze was mostly directed towards the centroid, such that mainly peripheral vision was being used to monitor the four targets. Thus, the novel MOT setup proved to be suitable for further research on the functionality of peripheral vision. The results of Experiment 2 showed, as predicted, higher detection rates and more peripheral detections for motion than for form changes. Participants' average saccade initiation to the target was regularly *after* the change event (i.e., after the 0.5 s period in which the motion or form change occurred). It should be further noted that the difficulty to detect the form and motion changes was controlled, such that detection did not differ in foveal vision. Therefore, the differences revealed cannot be ascribed to more potentially salient motion changes (see "task difficulty check" in Vater et al., 2016). In summary, these findings indicate that peripheral vision is naturally used to monitor multiple objects and to detect change events, especially motion changes.

Using peripheral vision for simultaneous monitoring and change detection

In the study just discussed, saccades regularly occurred *after* the completion of the change period. Therefore, the detection must have been achieved by peripheral vision. However, as participants were instructed to stop the MOT task and name the change target rather than the four targets that were initially highlighted, it remained unclear whether this saccade was performed due to the task switch (monitoring to detection task) or as an inevitable consequence of the detection task. Therefore, in a second study, conducted by Vater, Kredel, and Hossner (2017a), we asked participants to continue the monitoring task to the end of each trial rather than finishing the MOT task immediately after change detection. With this modification, a dual-task situation was created with a primary monitoring and a secondary change-detection task. If saccades were still performed under these conditions, they should be understood to be automatically induced by the change event for foveal detection; however, the absence of saccades would rather favor the participants' ability to continuously use peripheral vision to detect change events.

Experiment 1 of the second study aimed to empirically check the dual task situation. Participants were required to monitor four targets and simultaneously respond to motion or form changes by pressing a button (with no requirement to name the change target at the end of the trial). To further examine eccentricity effects, the distance of the target-change location to the centroid was manipulated so that changes occurred at either near (5-10°) or far (15-20°) locations. The results showed that motion changes were detected equally as often at near and far eccentricities, whereas form change detection remarkably decreased at far eccentricities. Furthermore, it should be noted that over 80 % of target changes at far eccentricities (in form or motion) were detected solely with peripheral vision. This finding highlights the successful use of peripheral vision to simultaneously detect target changes and monitor multiple objects.

In Experiment 2, we put an alternative explanation for the results of Experiment 1 to test: the impact of visual salience, i.e., the distinctiveness of object-related feature changes in the visual environment (Bruce & Tsotsos, 2009; for a model of saliency-based visual attention; see Itti, Koch, & Niebur, 1998). This experiment was motivated by the claim that, as argued above, higher detection rates for target stops might be because stops are "easier" to detect than 45° target rotations. Therefore, in Experiment 2, the detection of a (more salient) target stop was compared to a (less salient) target slowdown. If the results of Experiment 1 were only due to saliency, the same result pattern should be expected for Experiment 2. However, the findings reveal detection rate differences as a function of saliency but *no* interaction between change type (stop vs. slow-down) and eccentricity (near vs far). Hence, the alternative, saliency-based explanation for the results of Experiment 1 can be empirically ruled out. Rather, the originally proposed explanation can be retained: the superior detection rates of motion compared to form changes should be attributed to the capability of the peripheral-visual system to detect motion changes. Furthermore, the overall high detection rates underscore the great potential of peripheral vision to monitor objects and simultaneously detect change events – and especially motion changes – even at far eccentricities.

Effects of attentional and visual demands on performance and the use of peripheral vision

In sports-related literature, the notion is widely held that the achievements of the peripheral-visual system are closely linked to attentional processes, such as the capacity of athletes to appropriately "distribute attention" or make optimal use of "covert attention" (Ryu et al., 2015; Williams, Davids, & Williams, 1999, p.90f.). Accordingly, this link has been corroborated by many empirical supports. For example, attention has been shown to alter change-detection rates in MOT, with changes of unattended distractors missed more often than changes of attended targets (Bahrami, 2003; Sears & Pylyshyn, 2000). Furthermore, if covert attention is adequately located at peripheral locations, contrast sensitivity is improved (Carrasco, Ling, & Read, 2004; Gobell & Carrasco, 2005) and peripheral information is processed faster (Carrasco, Giordano, & McElree, 2006). Directing attention to relevant locations thus seems to facilitate task performance and "boost" the capabilities of peripheral vision. Hence, to identify how visual and attentional demands affect gaze behavior and performance in dual-task situations, these two demands were selectively manipulated in a third MOT study, conducted by Vater, Kredel, and Hossner (2017b).

For the visual manipulation, a so-called *crowding effect*, which is "one of the most characteristic traits of peripheral vision" (Strasburger, Rentschler, & Jüttner, 2011, p. 29), was created by temporarily bringing certain targets and distractors into close proximity. From a task similar to MOT that greatly depends on peripheral vision, previous studies have determined that crowding can be expected to increase tracking demands, consequently decreasing tracking performance (e.g., Franconeri, Lin, Pylyshyn, Fisher, & Enns, 2008). Besides crowding, attentional demands were manipulated by inducing target collisions with the bordering frame. Collisions have been noted to capture attention and regularly lead to saccades to the location of the collision (Elfanagely, Haladjian, Aks, Kourtev, & Pylyshyn, 2011; Fehd & Seiffert, 2010; Zelinsky & Todor, 2010). Hence, if attention is captured by a collision and thus is no longer distributed between all targets, motion changes of now unattended targets should be missed more often, deteriorating performance of the secondary detection-task in the introduced dual-task setup.

The obtained results demonstrate that in fact crowding impairs tracking accuracy and that collisions affect change-detection rates. Target-motion changes were missed more often if a collision occurred during the target-change phase. Results further indicate that, if targets are crowded by other objects, gaze is located closer to the group of crowded objects. This gaze attraction would presumably increase spatial acuity to thus better separate the crowded targets from the distractors. Regarding collisions, the analyses of saccades confirmed that collisions indeed capture attention. Saccades were generally initiated *before* a collision, indicating that attention must have been on the colliding target before the collision. The subsequent saccade is then presumably initiated to update target positions after the anticipated collision. Consequently, trials with anticipatory saccades had impaired change-detection performance compared to trials without saccades. This finding demonstrates the dysfunctionality of saccades, due to either an interrupted information pick-up (Burr & Morrone, 1996) or to changes of attentional allocation from all targets anymore to rather the saccade target (Kowler, Anderson, Dosher, & Blaser, 1995). In both cases, however, it can be inferred that saccades inevitably come with costs affecting the secondary change-detection task.

Overall, the third study conducted successfully determined how visual as well as attentional demands selectively affect change-detection rates and peripheral-vision usage. The results indicate that target monitoring is impaired when crucial objects are hard to separate from other objects with peripheral vision; therefore, it is helpful to anchor gaze closer to these crowded objects. The finding that saccades impair change-detection further substantiate the general dysfunctionality of saccades in dual-task situations, especially when detection of unpredictable target-changes is required. Thus, in situations similar to those here researched, an *optimal* gaze-anchoring position could be functional to avoid saccadic costs and the consequential reduced spatial acuity of peripheral vision.

Implications for sports-related research

The results of the laboratory research introduced above underline the functionality of peripheral vision to simultaneously process information from multiple moving objects. This processing allows one not only to monitor movements of multiple objects, but also to detect object-related events such as form or motion changes. It is important to note that, in our experiments, the detection of target changes neither induced modified gaze behavior nor affected primary task performance to great extents (e.g., see Vater et al., 2017a), further highlighting the functionality of peripheral vision in the examined situations of MOT.

Beyond their significance to fundamental research, the findings claim relevance to sports in two regards; namely considering (a) the pursued empirical approach to studying the natural use of peripheral vision, and (b) the derivation of further predictions on how perceptual task-demands might affect performance in the context of sports. In regards to the latter point, particular interest lies in how perceptual-motor performance depends on (b1) the kind of perceptual information to be processed, (b2) the perceptual surroundings of crucial objects, and (b3) the probability of the occurrence of events that require – beyond peripheral monitoring – foveal vision for the processing of detailed information. Below, we will discuss the theoretical and practical implications of these issues for sport science. Further, experiments that have been or will be conducted by our research group examining just these implications will be briefly introduced.

(a) Experimental approach to studying natural peripheral-vision usage in sports

The findings from our fundamental MOT research indicate that peripheral vision is naturally used to monitor a number of moving objects. In this context, "naturally" means that participants used a centroid- looking gaze behavior without the instruction to fixate on a central fixation cross. That participants are free to move their gaze is a great advantage, because it brings the experimental task closer to real-world situations and thus further appeals to sport-specific investigations. On the basis of these results, for sports tasks such as those requiring the monitoring of a ball and a number of players, it can be expected that peripheral vision is used to a great extent and that attention is accordingly distributed to these locations to process relevant information.

Although unnatural gaze instructions were successfully avoided, measuring the locus of attention in sports-specific settings presented a greater methodological challenge. For this purpose, based on the previous results, a secondary detection task could be combined with a decision-making task to determine whether peripheral vision is being used to process information with covert attention. As an example, the instruction for a striker observed in a 3 vs. 3 soccer decision-making task could be: "Decide whether you pass, shoot or dribble, depending on the actions of the other players. Play a pass as soon as you notice that one of your teammates makes a run to free space." In this task, the monitoring of relevant opponents and teammates is indispensable. Additionally, an action response is required, for which the processing of players' movements is crucial to making the appropriate decision for the pass. These kinds of investigations could be applied either on the field or in a laboratory setting that is conducive to gross-motor action responses. Moreover, to determine whether information was processed with peripheral rather than foveal vision, analyses of eye-movements in relation to action responses would be essential. If the pass was initiated before gaze was switched to the pass receiver, information clearly must have been processed peripherally. Assuming that information is processed before the initiation of a pass, a preceding pilot study with button responses instead of action responses would be beneficial to determine the processing latencies from the actual detection of a free player to the initiation of the pass.

In comparison to previous studies examining peripheral vision, the proposed experimental setup (i) does not require the masking of visual information (Mann et al., 2007; occlusion paradigm), (ii) should not disturb natural gaze behavior (Ryu et al., 2015; moving-window/mask paradigm), (iii) should not decrease decision making performance with a non-integrated secondary task (Ericsson & Simon, 1987; concurrent verbal reports), and (iv) should reduce potential effects on decision making caused by *a priori* expectations (Williams, Davids, & Williams, 1999), attempts to rationalize decisions (Green, 1995) or difficulties verbalizing decisions (Nisbett & Wilson, 1977; retrospective verbal reports).

(b1) Types of information and peripheral performance

From our fundamental findings, it can be predicted that (sufficiently salient) change events, especially motion changes, are well detected by peripheral vision. Thus, in sports, one would expect a player initiating a sprint to be detected better than a player initiating a slow walk at the same eccentricity. It is particularly noteworthy that the eccentricity, measured in degree of visual angle from the fixated location to the event of interest, should not notably affect peripheral detection of salient motion-related information within an eccentricity of up to (at least) 20° of visual angle (Vater et al., 2017a). Thus, anchoring gaze on the central opponent to monitor players moving on the right and left could indeed be functional for decision making (Williams & Davids, 1998). However, anchoring gaze *between* relevant locations has also been found to be beneficial (e.g., Vansteenkiste et al., 2014), especially for facilitating the information pick-up of relative motion between cue areas (Abernethy et al., 2001; Ward et al., 2002). Such an optimal gaze-anchoring position was determined by our research group for beach-volleyball defense (Hossner, Klostermann, Kredel, Lienhard, & Vater, 2017). In this study, expert beach-volleyball players' gaze behavior was examined with a motion-integrated eye-tracking system that allowed for quasi-natural action responses. In this laboratory setting, participants viewed video scenes from a first-person perspective and were instructed to reach cut shots or long-line shots before the ball hit the ground. For this task, information from the attacker and the ball could be expected to be the most relevant information locations (Vansteenkiste et al., 2014). The analysis of gaze behavior showed that expert players anchor their gaze close to the anticipated ball-hand-contact location (i.e., between the ball coming from above and the attacker coming from below) before initiating their motor response. Anchoring gaze at this location could facilitate parallel information pick-up from both cues, thereby avoiding the information-processing costs of late saccades and rather promoting the initiation of a timely motor response.

Interestingly, in the experimental *action* conditions of our beach-volleyball study, gaze was mainly located close to the anticipated ball-hand-contact position. These *action* conditions required participants to mimic a defense movement, whereas the experimental *verbal* conditions simply required participants to name the anticipated kind of attack. This finding might support the hypothesis that relevant information from multiple locations must be processed in order to initiate actions under high spatio-temporal demands. Therefore, from a methodological point of view, future research should identify relevant cues to determine to which locations attention should be distributed. Accordingly, the optimal gaze-anchoring position can then be predicted based on the particulars of the visual system. Specifically, if high spatial acuity is required to process information from a certain location, gaze should be located closer to this location. However, if motion-related information is foremost relevant, peripheral vision can be used and gaze can be anchored between multiple relevant locations. This also implies that, in future studies on vision in sports, gaze locations in "free space" (e.g., between the ball and the hand of the attacker in beach-volleyball) should *a priori* be identified as potentially functional positions and thus be included in analyses.

(b2) Object constellations and peripheral performance

In a soccer situation, a target player should be best peripherally detected if he or she is not surrounded by other players. Otherwise, the resulting crowding effect would theoretically decrease the possibility of separating the players from one other. If the target player is crowded by other players, additional attentional resources should be allocated to the crowded player for successful identification. These attentional shifts could either be overt (i.e., a saccade is initiated to a new location) or covert (i.e., gaze remains stable but attention is re-allocated). The latter shift in covert attention towards the crowded players could help to distinguish individuals, as the capabilities of peripheral vision can be improved by locating covert attention properly (Carrasco et al., 2004; Gobell & Carrasco, 2005). Therefore, especially in tasks with high spatio-temporal demands, one could benefit from an event-optimized gaze-anchoring position, in which gaze is located close to cues that require increased spatial acuity and that is accompanied by an optimal distribution of attentional resources. These gaze-anchoring locations might then be seen as advantageous "pivot points" (e.g., Williams & Elliot, 1999).

A good sports example of a task-dependent anchoring position arises in offside-decision making in soccer. From the perspective of the assistant referee, the offside-decision can be regarded as a dual-task situation. On the one hand, the player in possession of the ball must be monitored to precisely detect the timing of the critical pass to an attacker; while on the other hand, the location of the pass-receiver must be accurately perceived to determine the possibility of an offside situation (in which the player is closer to the goal than to the second-last defender, with the last defender generally being the goal keeper). Previous research has shown that assistant referees anchor their gaze on the offside line before and during the offside decision, suggesting that peripheral vision is used to detect the moment of the pass (Catteeuw, Helsen, Gilis, Van Roise, & Wagemans, 2009). Evidently, due to its high spatial acuity, foveal vision is functional for judging the spatial relationship between the second-last defender and the pass-receiver, explaining the referees' observed visual behavior. In our own study (Vater, Schnyder, Kredel, & Hossner, 2017), we further predicted that this gaze-anchoring strategy affects the pass-detection accuracy (i.e., the perceived timing of the final pass) as a function of the passer's eccentricity. Virtual-reality animations were created that allowed us to present the same situations at different eccentricities. Participants had to simultaneously decide whether it was offside or not and press a button as soon as the critical pass to the attacker was played. For the analysis, trials were included if the participant indeed fixated the offside line over the whole interval from the pass to the button press. As in the study by Catteeuw et al. (2009), the use of peripheral vision allowed participants to accurately detect the moment of the pass. The prediction that the detection of pass timing would be less accurate at greater eccentricities was confirmed; the difference between the moment of the actual pass and the moment of the button press increased with larger eccentricities. This result could potentially be explained by crowding effects of other players surrounding the player making the critical pass or the less sensitive motion perception at larger eccentricities.

(b3) Event probability and peripheral performance

Beyond the issues discussed thus far, it should also be considered that, in the highly complex world of sports, peripheral vision might not always suffice to successfully monitor multiple objects. In certain cases, saccades from one location to another and consequently, overt attentional shifts may be mandatory to gather crucial information. In terms of our aforementioned MOT results, these overt shifts are likely used to identify motion-direction changes, as saccades were typically initiated in cases of target collisions with the bordering frame. The fact that those saccades mainly occurred *before* the collision signifies that attention was already directed to the position of the subsequent fixation (Findlay, 1982; Nuthmann, 2014), and that, in this context, peripheral vision enables the visual system to prepare efficient saccades (Nuthmann, 2014; Ryu et al., 2015). However, the reported MOT findings also indicate that saccades come with costs of losing track of other target locations, due to the interrupted information processing (visual limitation) and the inability to distribute attention to all targets (attentional limitation), thus deteriorating detection rates of target changes (Vater et al., 2017b). Consequently, in situations that do *not* require foveal vision, it can be concluded that peripheral vision should preferably be used to detect target changes in the visual environment, especially since the monitoring of other relevant objects can be maintained.

Such a continuous monitoring of cues seems to be crucial, for instance, in martial arts, where attacks can be initiated from multiple locations and where short time windows for initiating defensive movements greatly increase the cost of eye movements (Ripoll, Kerlirzin, Stein, & Reine, 1995; Williams & Elliot, 1999). In our own study of martial arts (Hausegger, Vater, Kredel, & Hossner, 2017), it was predicted that the gaze-anchoring height on the opponent's body – as a measure of an event-optimized anchoring position – depends on the cue positions, meaning the possible attacking locations. Specifically, when attacks are expected from both the arms and legs, as is the case in Qwan Ki Do (QKD), gaze should be anchored higher than when attacks are mainly initiated from just the legs, as is in Tae Kwon Do (TKD). In a field study, in which expert QKD and TKD fighters wore a mobile eye-tracker and had to defend attacks from an opponent, gaze was indeed initially anchored higher in Qwan Ki Do than in Tae Kwon Do. These findings thus demonstrate that the anchoring location indeed depends on the peripheral monitoring of highly probable event locations.

Conclusion

In conclusion, peripheral vision is advantageous for tracking multiple moving objects in the environment and for simultaneously detecting changes that require an action response. Due to the relative perpetuation of peripheral vision to detection motions at larger eccentricities, gaze anchoring seems to be particularly functional for reacting to motion changes, especially if saccades have high costs as in highly time-constrained sports situations. Therefore, for sports practice, a distance- and event-optimized gaze-anchoring position can be recommended. Moving forward, the empirical justification of this recommendation should be tested in sport-specific settings to examine its benefit for motor performance in sports. Specifically, the attentional and visual demands of such settings should be considered to correctly assign gaze to specific cues and to better interpret gaze-behavior results accordingly. Further systematic manipulations of task demands, especially spatio-temporal requirements and event predictabilities, would substantially deepen the understanding of the functionality of gaze anchoring and peripheral-vision usage in sports.

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Data Availability Statement

All relevant data are within the paper.

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